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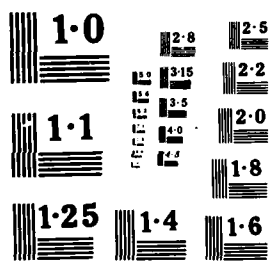   30 SEP 84 AFOSR-TR-86-0240 AFOSR-80-0026

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INTERIM SCIENTIFIC REPORT

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This research had two objectives: 1) to study the application of cryogenic technology to the problem of gravity gradient measurements, and 2) to use such a gradiometer to make more accurate measurements of the inverse square law of gravity to test the recent experimental and theoretical suggestions that the inverse square law of gravity might be violated at laboratory distances.

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INTRODUCTION

This research has had two objectives: (1) to study the application of cryogenic technology to the problem of gravity gradient measurements, and (2) to use such a gradiometer to make more accurate meaurements of the inverse square law of gravity to test the recent experimental and theoretical suggestions that the inverse square law of gravity might be violated at laboratory distances.

Since room temperature gradiometers are ultimately limited by room temperature Brownian motion, we have been experimenting with a laboratory cryogenic gradiometer which could lead to the development of a more sensitive moving baseline gradiometer for field use. Such gradiometers could have applications to problems in navigation and modeling of the earth's gravitational field.

Recently the inverse square law of gravity at laboratory distances has become a subject of great interest to physicists. This has come about for two reasons. First, Long[1] and more recently, Tuck[2] have found an apparent violation to the inverse square law of gravity at laboratory distances. If this were found to be correct, it would be one of the most important experiments in the history of physics. Secondly, theorists have begun to speculate on the possible existence of new fundamental particles which could affect the inverse square law of gravity at laboratory distances. For example, axions with mass 10^{-5} eV have been postulated to explain the dark matter of our galaxy and the reason for the lack of parity in time-reversal violation and strong interactions. Such particles could contribute to a violation of the inverse square law.[3] By making use of a superconducting gradiometer it appears possible to check the inverse square law at distances of the order of one meter to an accuracy of 2 parts in 10^5.

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Operation of a gravity gradiometer at 4 K offers a reduction of thermal noise power by a factor of 75 over that in room temperature environments, and this is the principle motivation for the development of cryogenic instruments. However, there are many other potential advantages which help to offset the additional effort required to maintain the instrument at 4 K. Below 10 K several metals lose all low frequency electrical resistance (superconductivity) and become nearly perfect magnetic shields. These materials are used in our gravity gradiometers to make magnetic readouts which are free of thermal noise. Although careful construction is required to allow for the thermal contraction of the instrument as it is cooled from room temperature to 4K, once the device is cold the coefficient of thermal expansion is far below the room temperature value. The liquid helium bath commonly used to maintain low temperature also provides a stable thermal environment. In addition, low frequency amplifiers of unequaled sensitivity based on the *Josephson effect* (SQUIDs) are commercially available.

During the early part of our work we constructed and tested two prototype gradiometers. These devices both incorporated superconducting coils and proof masses, were built with similar techniques, and both measured a single diagonal component of the gravity gradient tensor. They differed in the method used to obtain common mode balancing. One of our prototypes used four superconducting coils, one on each side of two superconducting diaphragms. Each pair of coils and diaphragm produced a current in response to an applied acceleration, and these two currents were subtracted at the input of a SQUID. We referred to this gradiometer as "current differencing". Our second prototype used a single coil located between two superconducting proof masses so that its inductance was modulated only by relative motion of these two proof masses. We called

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this gradiometer "displacement differencing". Because the four coils in the current differencing gradiometers are not perfectly matched, the overall balancing problem in this gradiometer is more complicated. Consequently, we choose the displacement differencing design to an improved version.

We have completed construction of this improved gradiometer and operated it at 4.2 K with sensitivity approaching $1E/\sqrt{Hz}$ at frequencies between 2 and 10 Hz. In order to achieve this level of sensitivity at lower frequencies, a new cyrostat probe was built to provide a 1.3 K environment for the gradiometer. The purpose of this was to reduce the thermal sensitivity of the instrument. In addition, the new probe was designed to provide a high degree of seismic and magnetic isolation. This probe will be used to gather data from the gradio-meter during the inverse square law experiment.

II. Description of the Gradiometer

Our primary goal in the design and fabrication of our gravity gradiometer was to minimize the instrument's sensitivity to linear accelerations both along the proof mass direction and perpendicular to it. Linear accelerations in the laboratory exert forces on the proof masses which are very large compared to the gravitational forces we would like to measure, so careful balancing of the gradiometer is needed to eliminate them as a noise source,

In addition, we decided to build an on-line gradiometer which measures one of the diagonal components of Γ. It is highly desirable to be able to measure all three components of $\nabla^2 \phi$ so we chose a method for suspending the proof masses which allows us to operate the gradiometer with its sensitive axis vertical as well as horizontal.

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In order to make the balancing problem manageable we chose a mechanical design which enabled us to use only one coil in the readout system described later. Experiments have been done with readouts using several coils, but in these gradiometers careful matching of the coils as well as the proof masses is necessary to reject linear accelerations.

Basically the gradiometer consists of two superconducting proof masses adjacent to each other. A single niobium coil is mounted in the gap between the proof masses so that the coil inductance is proportional to their spacing. This readout system is analyzed in detail below. Since the sensitive axes of the proof masses are parallel, the gradiometer detects changes in one of the diagonal components of the gravity gradient tensor, Γ_{jj}.

Each of the two proof masses is supported with two mechanical springs. The mechanical springs are folded cantilevers cut into circular disks of niobium. A folded cantilever with two-fold symmetry is shown in figure 1. In this case the thickness of the plate is reduced in the two rectangular areas hatched in the figure in order to restrict the bending to those areas. Slots are then cut in the indicated locations. These slots allow the center to move perpendicular to the plane of the plates as shown in the lower part of the figure. Since the center of the spring is free to move in the plane of the plate, the total length of the spring remains constant and the restoring force is provided by pure bending without stretching of the spring material.

The proof mass subassembly consists of two springs, two cover pieces, an annular mass, and a ring used to hold the edges of the springs apart. The cover pieces are circular disks of niobium 8.51 cm in diameter which are flat on one side and have a threaded stud on the opposite side. The flat sides are designed to modulate the inductance of the readout coil or tuning coils described later.

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The flats were polished to ensure flatness and isotropy so that close spacing to the coils could be obtained, and so that the inductance of the coils is modulated only by linear motion of the surfaces. The threaded studs screw into an annular disk of niobium which provides the bulk of the mass for each proof mass. A spring is captured between each cover piece and proof mass. An exploded view of one of the two proof mass subassemblies is shown in Figure 2. The ring which is used to maintain the spacing of the edges of the springs is thicker than the proof mass so that each spring is biased away from its equilibrium position and never passes through its zero point. This eliminates certain forms of nonlinear behavior, Since the springs have opposite biases, the first order nonlinear terms also cancel. The ring was grounded to its final thickness to keep its two sides parallel to one part in 10^5.

Once the two proof mass subassemblies were constructed, they were stacked on top of each other with a ring holding them apart. The thickness of the ring was chosen so that the readout coil is about 0.013 cm from the opposite proof mass. This structure was mounted on an aluminum fixture which maintained the angular orientation of the parts. A niobium housing tube 9.3 cm long with a 10.5 cm inside diameter was placed over the parts (Figure 3).

The assembled gradiometer has been tested at 4.2 K and has performed as expected in the frequency range from 2 Hz to 10 Hz. It has now been incorporated in a new cryostat probe capable of cooling the instrument to 1.3 K.

III. Current Progress

In the past year we have completed construction of all major components of the inverse square law experiment (Figure 4). These include a 1.3 K cryogenic probe and a pedestal which is used to mount the cryostat in a ten foot hole in the floor. A pumping line is incorporated into the pedestal which will allow us to continuously pump on the cryostat to maintain the temperature of the
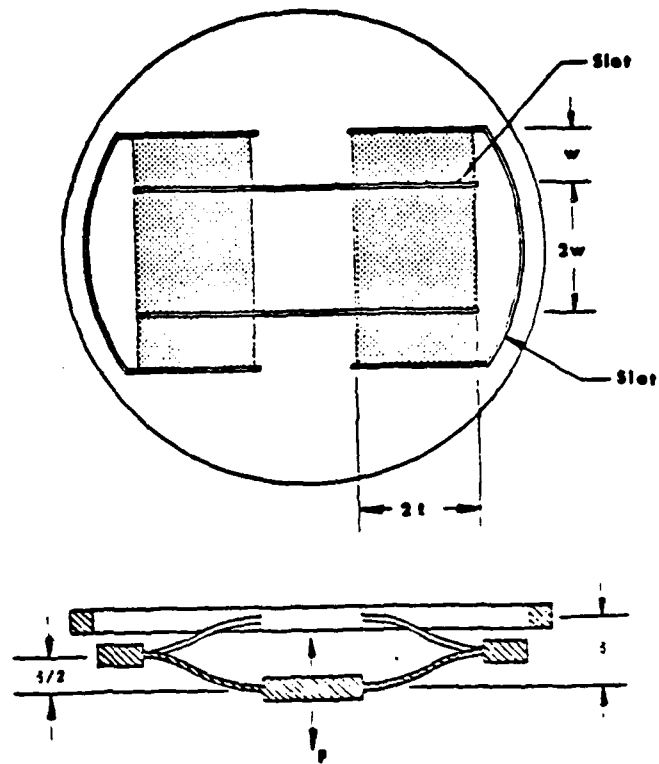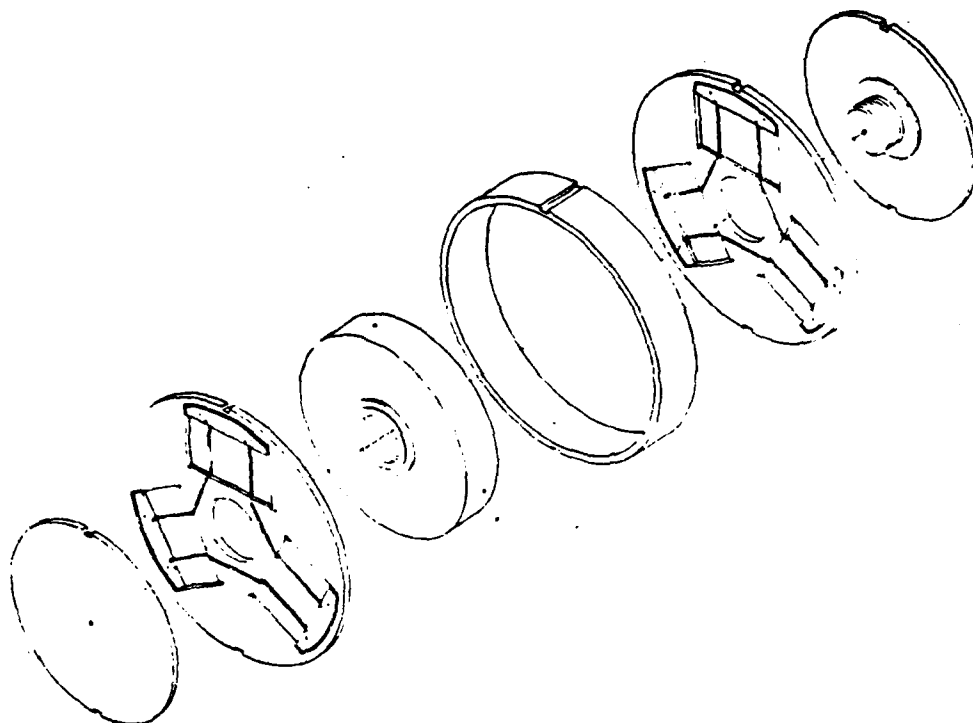
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Figure 1. Folded Cantilever Spring

Figure 2. Exploded View of a Proof Mass Subassembly

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Figure 3   Assembled gradiometer in mounting fixture. Mounting fixture includes flex hinges on both sides of the gradiometer so that the instrument may be tilted slightly by PZT bender plates (upper center).

Figure 4   Major components of the inverse square law experiment. The cylindrical test mass is shown in the upper and central portion of the picture and the dewar on its pedestal is barely visible at the bottom.

Figure 5   Upper and mid-portion of the new cryostat probe. Cold plate and the upper part of the 1.3 K radiation shield are at the very bottom. The isolation stack (which would be at the very top) is not included at this level of assembly.

Figure 6   Lower detail of the 1.3 K cryostat probe including the gradio- meter and its fixture in the lower portion of the picture. The plate in the central portion is a 1.3 K continuous cold plate refrigerator. During operation the gradiometer is completely enclosed by copper radiation shield attached to the cold plate. In turn the entire lower portion od the probe is isolated from the 4 K helium bath by a vacuum can sealed onto the top plate seen in the upper part of the picture.

Figure 7   Mechanical isolation stack. This assembly sits on top of the cryostat and provides the sole mechanical support for the gradio- meter. During operation, the stack is enclosed in a vacuum can.
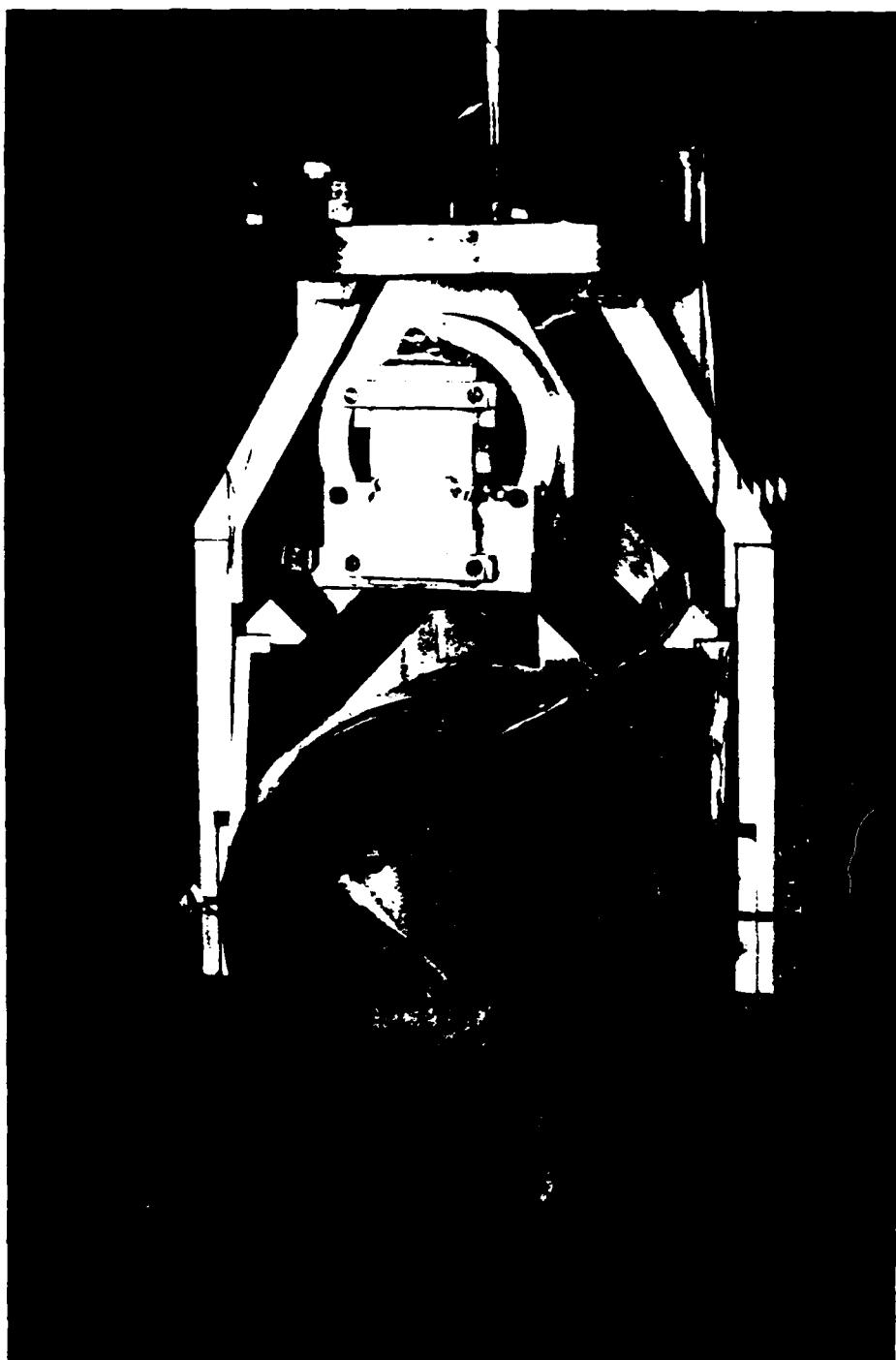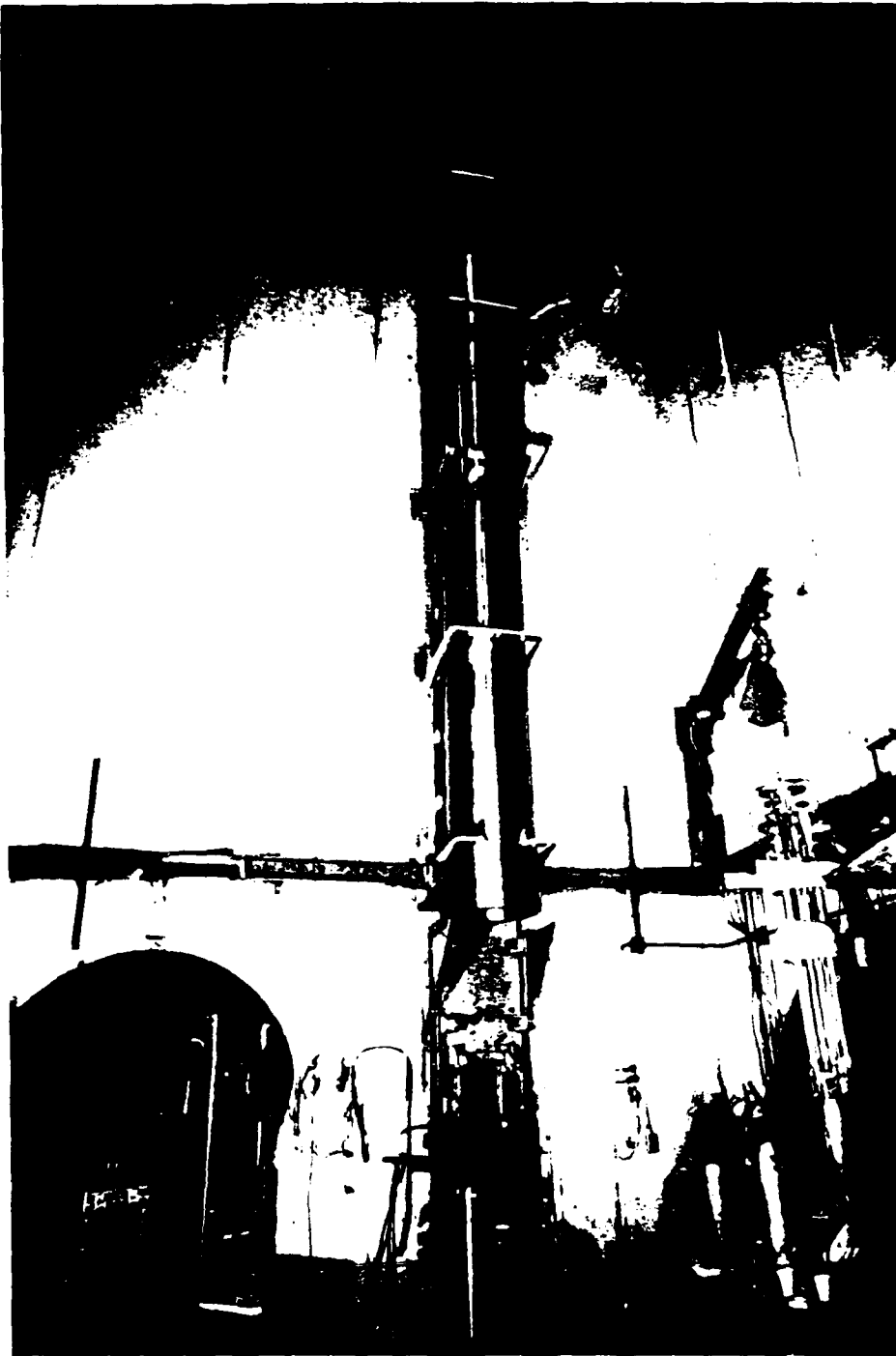
Figure 3

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Figure 4
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gradiometer at 1.3 K while the cylindrical source is moved up and down over the cryostats. The final major piece of the apparatus is the system for moving the cylinder up and down.

In order to maintain the gradiometer at 1.3 K, the new probe has a copper plate inside of the vacuum can which serves as a refrigerator (Figure 5). The probe vacuum can is immersed in a liquid helium bath at 4.2 K. The copper plate inside the can is thermally isolated from the can and contains a small reservoir which is connected to the 4.2 K bath through a flow impedance (Figure 6). This reservoir is continuously pumped to maintain the plate at 1.3 K. The flow impedance is adjusted at room temperature to adjust the temperature of the plate. The gradiometer is thermally grounded to this plate to operate it at 1.3 K. The cold plate has been tested successfully. It has the major advantage that liquid helium can be added to the bath in the usual way without disturbing the 1.3 K space. This means that the 1.3 K space can be maintained for long periods.

A second major improvement in the new probe is the addition of a mechanical transmission line which will isolate the gradiometer from vibrations at frequencies above 10 Hz (Figure 7). This line consists of four brass disks which hang from each other with small latex springs. The soft springs cut off vibrations above a frequency of about 10 Hz. The gradiometer hangs from the bottom of this stack by a stainless steel tube which allows the gradiometer to be at 1.3 K while the stack is at room temperature. The entire assembly is in vacuum to isolate from acoustic noise.

In order to measure the gradient at the center of the cylindrical gravitational source, the dewar containing the probe and the gradiometer has been mounted on a pedestal which will fit inside of the cylinder. The pedestal is mounted at the bottom of a ten foot deep hole which the cylinder is lowered into during
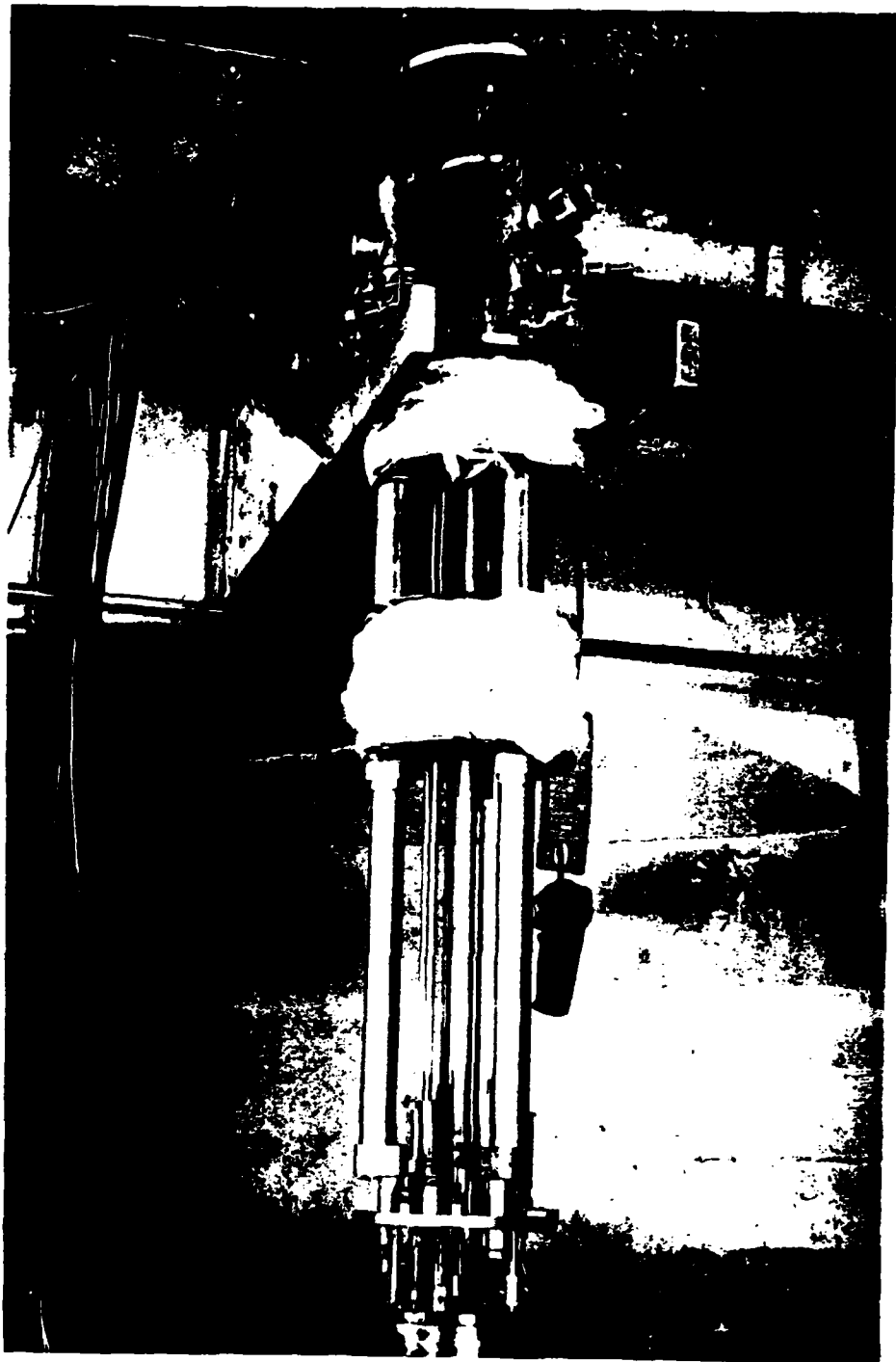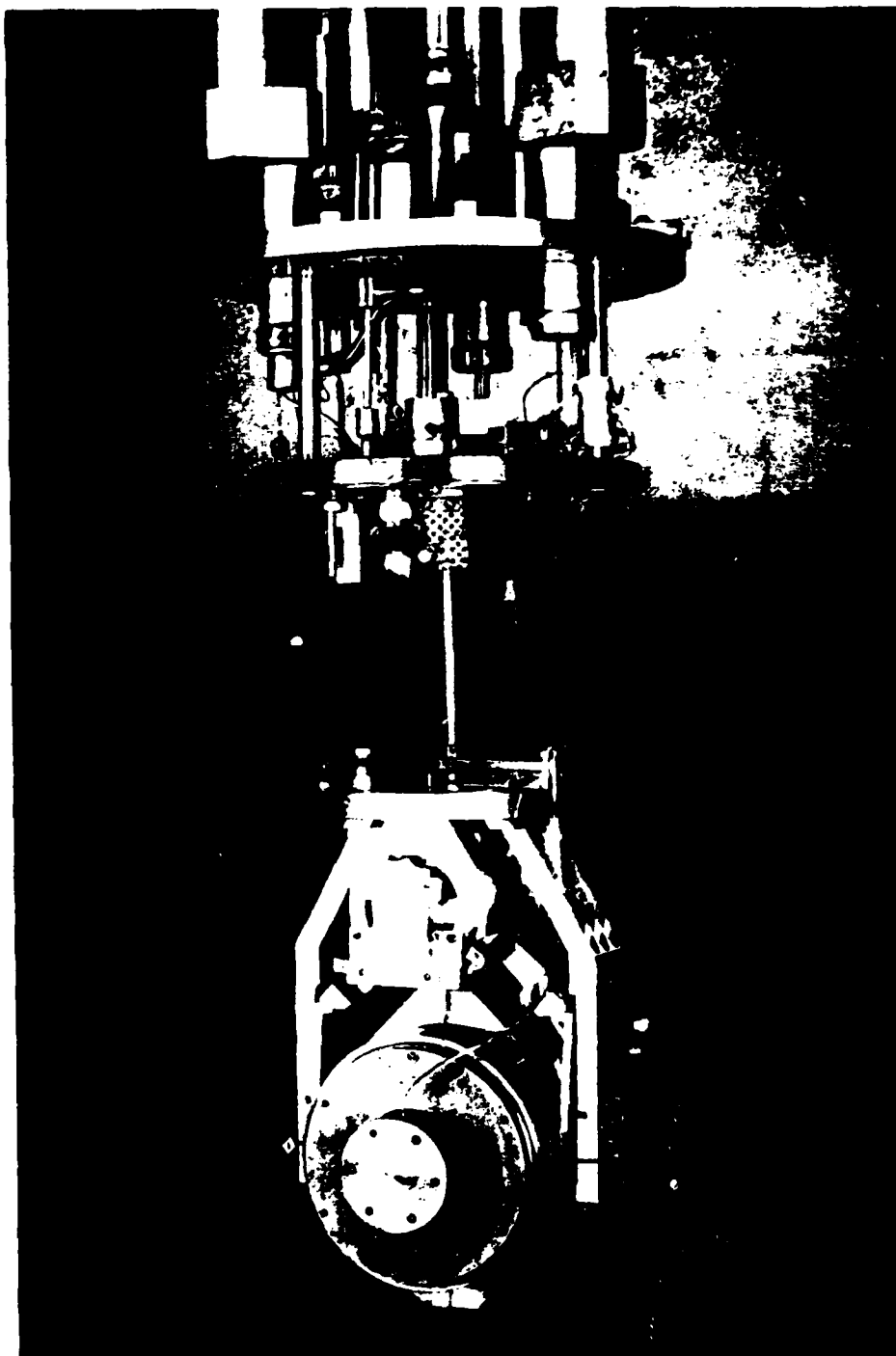
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Figure 5

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Figure 6
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Figure 7

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the measurement. This leaves the dewar near floor level to facilitate adjustments. A pumping line is built in so that the cold plate can be pumped continuously as the cylinder goes up and down. The 7,160 pound cylinder rolls along to steel I-beam up and down the wall of the end station in which the experiment will take place. A hoist has been installed to raise and lower it. Considerable care has been taken to ensure smooth motion of this large mass, and to minimize the vibration which the gradiometer must tolerate during the experiment.

During the past year the completed gradiometer and 1.3 K cryostat assembly has been subjected to initial tests. During these tests gradiometer output power spectra were obtained with the gradiometer in unbalanced operation. (Balanced operation was not possible due to inability to store sufficient current in the balancing circuit. This problem is presumed to be due to ohmic heating in the current supply leads which have been subsequently improved.) The output power spectrum obtained at 1.3 K was observed to have two distinct regions. Above about 0.2 Hz the spectrum was dominated by externally driven mechanical motion of the gradiometer, most notably the pendulum modes of the suspension system. Previous experience with the gradiometer has indicated that this response is reduced by a factor of ~1000 when the gradiometer is properly balanced. Below ~0.1 Hz the power spectrum was dominated by low-frequency-divergent behavior arising from the temperature coefficient of the gradiometer together with temperature fluctuations of the device. In the frequency range of interest for the inverse square law experiment (~0.15 Hz) the noise power is estimated to 30-40 $E/\sqrt{Hz}$ where a calibration factor obtained from operation at 4 K is used. Proper balancing of the gradiometer should drop this to a SQUID noise limited value of 1 $E/\sqrt{Hz}$. Further reduction of this value by an order of magnitude seems possible by the use of a dc SQUID which is now commercially available.

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Although the maximum frequency at which temperature fluctuations dominate the noise power spectrum has been shifted downward from 1 Hz at 4 K to 0.1 Hz at 1.3 K, the temperature coefficient at the lower temperature is higher than expected. In addition, temperature fluctuations at the gradiometer are on the order of 10 mK, much larger than what is possible to obtain. We have tentatively identified a free-floating radiation baffle located on the gradiometer suspension rod between the cold plate and the top of the vacuum can as a possible source of this problem. We are in the process of mounting a heater and thermometer on this baffle in order to be able to check this hypothesis and will be able to do so as soon as a leaking low-temperature feedthrough seal is replaced.

IV. Future Developments

In the following year this research will be continued with the aid of a fourth-year graduate student who will be visiting with Professor Ho Jung Paik from the University of Maryland. Our goal is to check the inverse square law to the highest possible accuracy and understand as well as control the temperature coefficient which remains at 1.3° K.

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